Historical Case Studies of Energy Technology Innovation

CASE STUDY 2: TECHNOLOGY DIFFUSION.

HISTORICAL DIFFUSION AND GROWTH OF ENERGY TECHNOLOGIES

Charlie Wilson
Tyndall Centre for Climate Change Research, University of East Anglia

AUTHORS' SUMMARY

Over the course of the 20th century, a range of both energy supply and energy end-use technologies have diffused widely throughout the energy system. Unit capacities of many energy technologies have also increased. The industry level growth (diffusion) and the unity level growth (up-scaling) varies spatially as technologies move out of their initial markets in which they are first commercialised to spread through later adopting regions. Analysing these historical growth dynamics at both industry and unit levels reveals some general patterns that appear robust across very different energy technologies.

At the industry level, the extent to which a technology's installed capacity grows is consistently related to the time duration of that growth. The consistency of this extent - duration relationship holds as technologies diffuse spatially, although the relationship steepens in later adopting regions as diffusion accelerates. At the unit level, increases in the unit size of a technology follow a lengthy formative phase of experimentation with many smaller-scale units. Subsequent up-scaling is most characteristic of technologies with clear economies of scale servicing homogeneous market segments. There is no evidence, however, to support an acceleration in this up-scaling phase as technologies diffuse spatially. These observed patterns have important implications, not least in striking a cautionary note on pushing for significant jumps in unit size before a 'formative phase' of experimentation with smaller-scale units.

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1 ANALYSING CROSS-TECHNOLOGY DIFFUSION DYNAMICS

1.1 Introduction

Over the past 100 years, global primary energy consumption has increased almost 10-fold (see also p229, Smil, 2000). In the 1960s, roughly one coal-fired steam turbine unit averaging 125 MW in capacity was installed every other day, and around 3 in 4 of these were in OECD countries alone. In the 1990s, Boeing and Airbus' combined production was about 3 commercial jet aircraft every other day carrying the equivalent of around 150 MW of power plant.

The ever-expanding capacity of the energy system to convert primary energy into energy carriers into useful services (and thence into human welfare) is thus driven by increasing numbers and increasing sizes of energy technologies: more coal power plants and jet aircraft; larger capacity coal power plants and jet aircraft.

These wholesale transformations of the energy system over the 20th century, on both supply- and demand-sides, are typically characterized at the industry level. As a current example, frequent reference is made to the double digit growth rates of the wind or solar photovoltaic industries (IEA, 2008). The headline growth in these technology industries in turn comprises, or is supported by, growth in related industries of materials, components, control systems, installers, business services, and so on - all part of inter-dependent technology clusters (Grubler, 1995).

For many energy technologies, growth at the industry level has been complemented by increases in the size or capacity of the technological unit itself. These unit level changes have been referred to as 'up-scaling' (Luiten and Blok, 2003). Figure 1 uses coal power and passenger jet aircraft as examples (see also p229, Gardiner, 1983). Steam turbine units in coal-fired power plants in OECD countries rarely exceeded 200MW for the first fifty years of their commercial deployment, before up-scaling rapidly in the 1950s and 1960s to the 1000 MW range. In the case of jet aircraft, Boeing's defining 707-100 model, certified for commercial flight in September 1958, carried 110 – 140 passengers a range of around 6,700km. The introduction of the Airbus A380 in 2007 was the most recent up-scaling of aircraft capacity, carrying 555 – 822 passengers a range of over 15,000km. The corresponding increase in engine capacity, expressed in MW terms, has been from 70MW to around 300MW. (For details of the kN thrust to MW conversion, and full details of all data sources, see Wilson, 2009).

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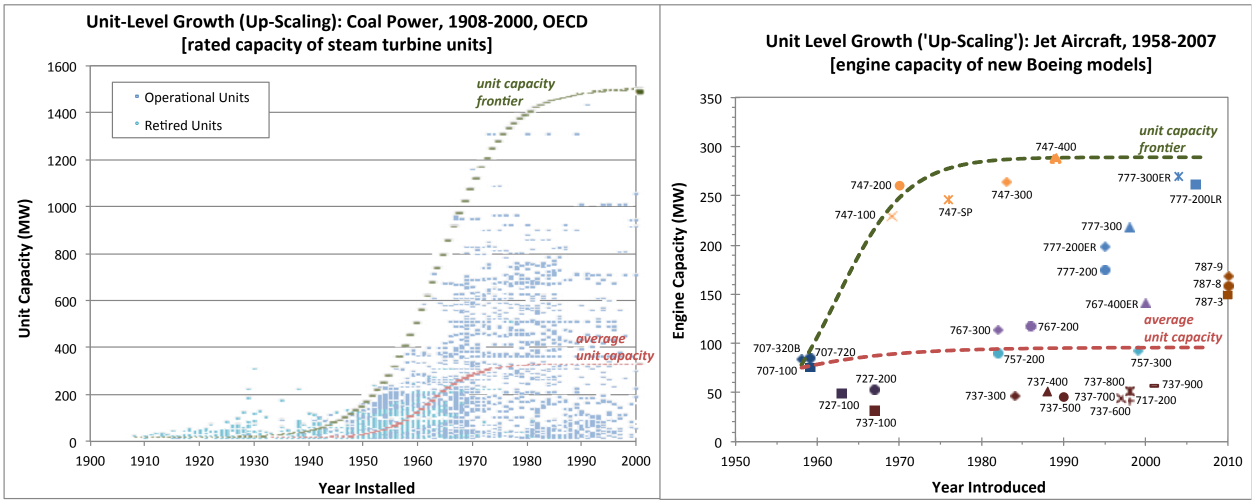

FIGURE 1. UNIT LEVEL GROWTH OR 'UP-SCALING' OF ENERGY TECHNOLOGIES: STEAM TURBINE UNITS IN COAL-FIRED POWER PLANTS, 1908-2000, OECD (LEFT PANEL); JET AIRCRAFT, 1958-2010, GLOBAL (RIGHT PANEL). NOTES: MAIN DATA SOURCES INCLUDE JACKSON, 1998; PLATTS, 2005; SEE ALSO WILSON, 2009 FOR DETAILS.

1.2 Aim & Method

This case study examines the historical record for regularities in the industry level growth (diffusion) and unit level growth (up-scaling) of a representative sample of energy technologies. Of particular interest is the relationship between industry level and unit level growth, and how this may change as technologies diffuse out of their initial markets. Common patterns observed should allow forward-looking inferences to be drawn about energy technologies and related policies.

Table 1 provides a simple illustration of the industry and unit levels using wind power as an example. The plant and system levels are included for the complete picture.

TABLE 1. WIND POWER GROWTH DISTINGUISHING UNIT, PLANT, INDUSTRY & SYSTEM LEVELS.

Level	**Wind Power Example**	**Observed Growth Dynamics Over The Past 30 Years**
Unit	wind turbine	Maximum turbine capacities installed each year have increased from the kW range to 3 - 5 MW, with further increases anticipated as installations move into the emerging offshore market niche.
Plant	wind farm	Wind farms combining turbines with balance of system components (e.g., transformers, grid interconnects) have increased in maximum capacity from the low MW range to many hundred MW arrays.
Industry	wind industry	Wind industry growth, measured as the annual % change in total installed capacity, is consistently double digit. Behind this capacity growth is an increasingly consolidated and globalised sector of turbine manufacturers, component suppliers (e.g., generators, gearboxes), and service industries (e.g., insurers, financiers) with localised assembly operations.
System	electricity system	Despite rapid growth, the wind industry is a small niche within continually expanding electricity systems comprising centralised & decentralised generation, transmission and distribution infrastructures, and proliferating numbers of electrical end-use technologies.

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1.3 Data

Historical time series data on industry level diffusion and unit level up-scaling were collected for a sample of energy technologies, ranging from centralised, capital intensive energy supply technologies to distributed, low cost technologies directly providing useful services to end users (see Table 2). Energy supply technologies included refineries, large scale power plants (coal, nuclear, hydro, natural gas), and small to medium scale power plants (wind, hydro). End-use technologies included jet aircraft, cars, and compact fluorescent light bulbs. Additional technologies were sampled (solar PV, mobile phones) but excluded from the analysis as their relatively early stage of diffusion meant overall dynamics were not yet observable.

Energy conversion capacity expressed in MW was used as a common metric of both industry level and unit level growth to allow cross-technology comparisons. In all cases, capacity data meaningfully related to the service provided by the technologies (e.g., the horsepower of cars and the thrust of jet engines relate to the mobility service provided). Industry level growth was expressed in terms of cumulative total capacity; unit level growth was expressed in terms of both average and maximum unit capacities.

Table 2 shows the time series data used in the cross-technology analysis, ordered from high to low unit capacity. In all cases, the time series data begins with the first commercial application of the technology through to the present. Detailed explanations and plots of all the data can be found in Wilson, 2009. (All data are also available online at http://www.iiasa.ac.at/web/home/research/researchPrograms/TransitionstoNewTechnologies/Scaling-Dynamics-of-Energy-Technologies1.en.html).

TABLE 2. HISTORICAL ENERGY TECHNOLOGIES ANALYSED. NOTES: SEE WILSON, 2009; WILSON, 2012 FOR DETAILS AND DATA SOURCES.

Technology	Time Series	Regions with Logistic Growth *(included in analysis)*				Regions with Non-Logistic Growth[a] *(excluded from analysis)*
		Global	Core	Rim	Periphery	
Oil Refineries[b]	1940-2000	Global	OECD +FSU	Middle East, Asia (ex. China), L.America	China, Africa	-
Coal Power	1908-2000	Global	OECD	(1) FSU	Middle East+ L.America+Africa	Rim
Nuclear Power	1956-2000	Global	OECD	(1) FSU	-	Rim, Periphery
Hydro Power	1900-2000	Global	OECD	(1) FSU	-	Rim, Periphery
Natural Gas Power[b]	1903-2000	Global	OECD	(1) FSU (2) Asia	Midde East+ L.America +Africa	
Wind Power	1977-2008	-	Denmark	-	-	Global, Rim, Periphery
Passenger Jet Aircraft[c]	1958-2007	Global	Boeing	Airbus	-	Periphery
Passenger Cars	1900-2005	Global	US	(1) FSU (2) OECD ex. US	-	Periphery
Compact Fluorescent Light Bulbs	1990-2003	-	N.America +W.Europe	-	-	Global, Rim, Periphery

[a] Either growth still in exponential phase reducing reliability of logistic fit, or insufficient data.
[b] For technologies with distinct, sequential phases of growth, logistic functions were fitted to the '1st phase' of growth if it evidenced a clear plateau.
[c] Boeing sales used as proxy for core region; Airbus sales for rim region; Boeing & Airbus combined for global data.
Acronyms: OECD = Organization of Economic Cooperation and Development (corresponding to developed countries); FSU = former Soviet Union (corresponding to economies in transition); L.America = Latin America.

1.4 Logistic Growth Functions

Growth function parameters were used to compare the extents and durations of industry level growth between different technologies. Logistic or S-shaped growth functions were fitted to the data subject to criteria of accuracy (minimum R^2 = 95%) and reliability (minimum % of estimated asymptote reached by data = 60%). Details of the logistic function are shown in the Box below.

Time series data which were not logistic in form and so were excluded from the analysis are shown in Table 2. For full details of the logistic function fitting, and its rationale, see Wilson, 2009; Wilson, 2012b.

BOX. THREE-PARAMETER LOGISTIC FUNCTION DESCRIBING S-SHAPED GROWTH.

$y = K / (1+e^{-b(t-t0)})$ and $\Delta t = \log 81 . b^{-1}$
with:
K = asymptote (saturation level)
b = diffusion rate (steepness)
Δt (delta t) = time period over which y grows from 10% to 90% of K
$t0$ = inflection point at $K/2$ (maximal growth)

We used two logistic function parameters in our analysis (see Box):

- K, the asymptote parameter, as a measure of the *extent* of growth;
- Δt, the time between 10% and 90% of the asymptote, as a measure of the *duration* of growth.

1.5 Spatial Disaggregation

Global data were disaggregated into four regions to account for the diffusion of technologies from their initial market of first commercial application through to subsequent and then final markets. These regions were defined for each technology by the sequence of spatial diffusion in the data. These regions are labelled 'core', 'rim' and 'periphery' in that sequence (following Grubler, 1998). Thus, for example, Denmark is the core region for wind power; the US is the core region for cars; the OECD is the core region for natural gas power. As the former Soviet Union presented a particular case historically with the sequence of diffusion relative to Western markets being either broadly concurrent (e.g., nuclear power) or markedly subsequent (e.g., solar PV), the 'rim' region was split into 'rim1' corresponding to the former Soviet Union and Eastern European countries, and 'rim2' corresponding to the remainder (see Table 2).

1.6 Overview of Analysis

The analysis is divided into three sections. The first section observes how rapidly and how pervasively energy industries have grown historically using energy conversion capacities as a metric. (For further details on both method & findings, see Wilson et al., 2012). The second section considers the relationship between unit level growth and this industry level growth, focusing on the characteristic 'formative phase' of experimentation and learning which precedes the main industry growth phase. The third section characterises the unit level growth or up-scaling in more detail, looking at changes in both average and maximum unit capacities. (For further details on both method and findings, see Wilson, 2009**;** Wilson, 2012b). The first and third sections also explicitly consider whether patterns observed are robust as technologies diffuse spatially out of their markets of first commercialisation.

2 FINDINGS: INDUSTRY LEVEL GROWTH

2.1 Consistent Cross-Technology Relationship between Extent and Duration of Diffusion

Figure 2 (left panel) shows the historical data series of cumulative total capacity for the 9 energy technologies analysed (note log-scale y-axis). These data describe the capacity expansion of each technology in its core region or initial market of commercial deployment (see Table 2 for details). Fitted logistic functions to these cumulative total capacity data then allow the extent and duration of industry level growth to be compared for different technologies. Figure 2 (right panel) shows the normalized K as a measure of *extent* of diffusion plotted against Δt as a measure of *duration* of diffusion (note log scale y-axis). K is normalized to account for changes in the size of the energy system into which each technology diffused. (For details of the method, see Wilson et al., 2012).

In general, a technology should take longer to diffuse to a greater extent notwithstanding the many factors that affect growth (Grubler et al., 1999). Figure 2 supports this finding, demonstrating a consistent extent – duration relationship between historical energy technologies of markedly different characteristics and vintage.

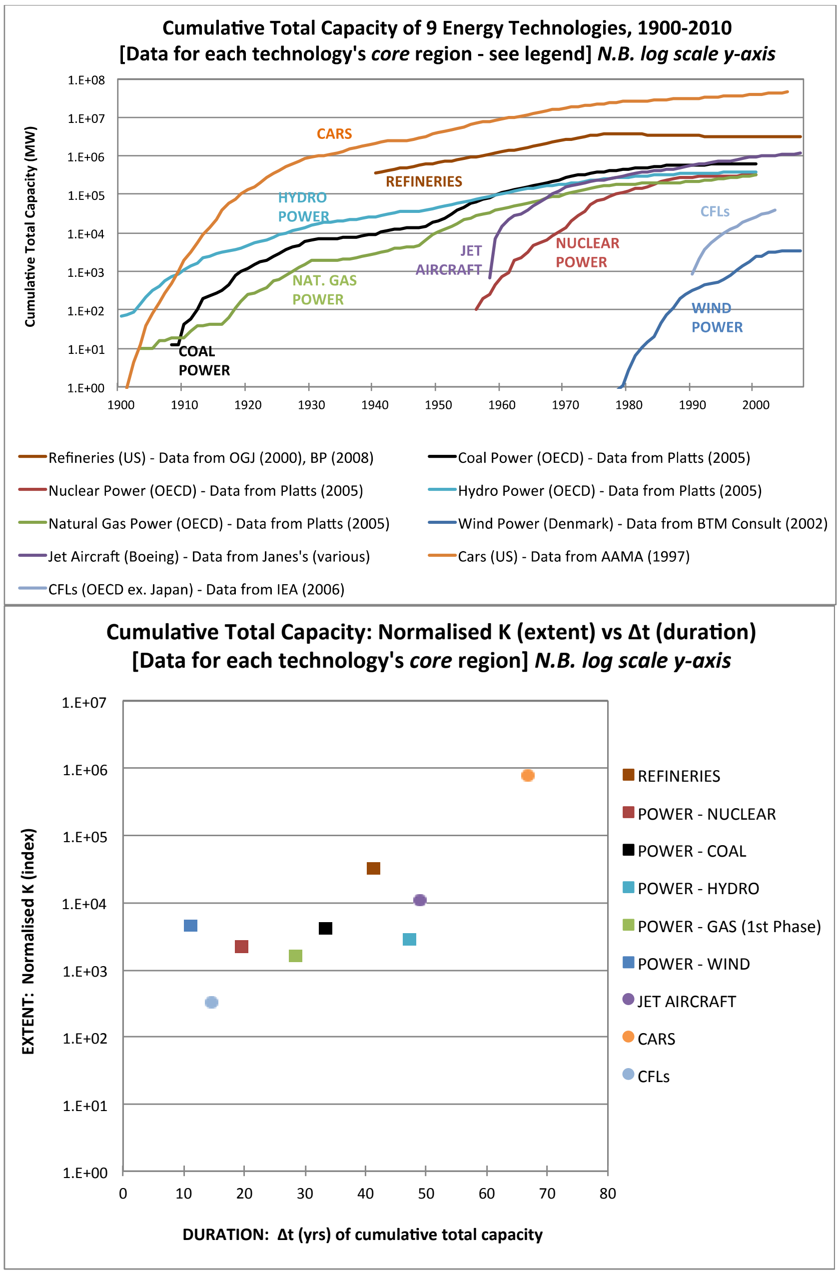

FIGURE 2. CAPACITY GROWTH OF 9 ENERGY TECHNOLOGIES IN THEIR RESPECTIVE CORE REGIONS. NOTES: TIME SERIES DATA (TOP PANEL); LOGISTIC FUNCTION PARAMETERS K VS. ΔT (BOTTOM PANEL). SEE FIGURE LEGEND & WILSON ET AL., 2012 FOR DATA SOURCES.

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The extent – duration relationship of growth in cumulative total capacity describes the energy system's ability to accumulate energy conversion potential over time through the manufacture and installation of capital stock. Refineries, power plants, jet aircraft, cars and light bulbs are characterized by different energy service demands, and have distinctive costs and efficiencies, capital intensiveness, turnover rates, regulatory contexts, implications for infrastructure, and so on. Yet observed consistencies between extents and durations of capacity growth historically suggest influences on diffusion act *proportionately* on both extent and duration, so preserving the relationship seen in the extent - duration relationship plots (bottom panel, Figure 2).This cross-technology consistency in the historical relationship between extent and duration of industry level growth describes the inherent inertia of a large, complex, inter-related system of technologies, infrastructures and institutions (Unruh, 2000; Wilson and Grubler, 2011).

2.2 Shorter Duration but Less Extensive Growth as Technologies Diffuse Spatially

As technologies diffuse spatially from initial (core) into subsequent (rim, periphery) markets, knowledge spillovers can lead to an increase in the speed of diffusion. However, this tends to be associated with a decrease in the pervasiveness of diffusion, measured, for example, as lower saturation densities. This general pattern of spatial diffusion being associated with more rapid but less pervasive growth is known as Schmidt's law (Grubler, 1990).

Figure 3 shows Δts (as a measure of the duration of diffusion) for the 9 energy technologies analysed as they diffuse spatially through the sequence from core, rim1, and rim2 to periphery regions. Omitted bars mean data were either unavailable or data described exponential growth which was not yet clearly identifiable as logistic (see Table 2). As logistic growth is symmetrical about the inflection point at which growth rates are maximal, the duration of diffusion is inversely related to the rate of diffusion. Thus longer durations (high Δts) indicate slower rates.

The basic pattern observed in Figure 3 confirms Schmidt's Law, and by implication, the effect of knowledge spillovers as technologies diffuse spatially. Durations of industry level growth tend to decrease (or rates of growth increase) from core to rim to periphery regions.

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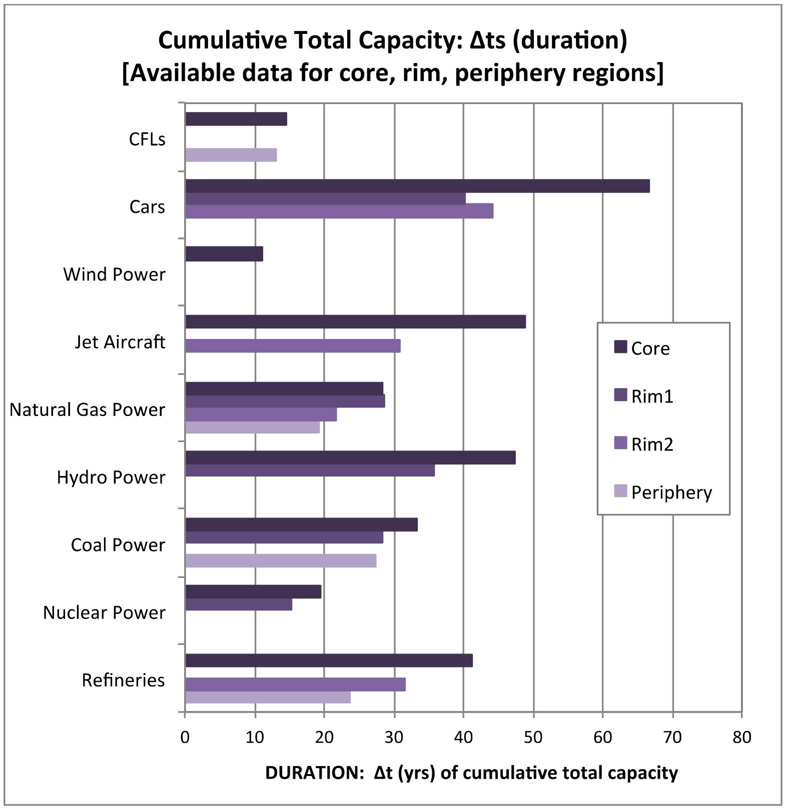

FIGURE 3. DURATION OF CAPACITY GROWTH AS TECHNOLOGIES DIFFUSE SPATIALLY. NOTES: BARS SHOW ΔTS OF INDUSTRY LEVEL GROWTH IN EACH TECHNOLOGY'S CORE, RIM1, RIM2 AND PERIPHERY REGIONS. OMITTED BARS MEAN DATA WERE UNAVAILABLE OR DID NOT DESCRIBE LOGISTIC GROWTH. SEE WILSON, 2009 FOR DETAILS.

The accelerating rates of growth are shown more clearly in Figure 4 which plots logistic growth functions fitted to the data for each region on the same y-axis scale, by indexing each function's asymptote parameter (K) to equal 1.00. The rate (steepness) and timing (position of curve on the x-axis) can be readily compared for core, rim1, rim2 and periphery regions. Three technologies are illustrated: refineries, natural gas, and passenger cars. In the cases of refineries and natural gas, the logistic functions describe a 1st phase of growth which culminated in a period of saturation (slow / no growth) following the oil shocks in the 1970s. For each of the three technologies, diffusion in the core region (blue line) is less rapid (flatter curve) than diffusion in the later regions (red, green, purple lines).

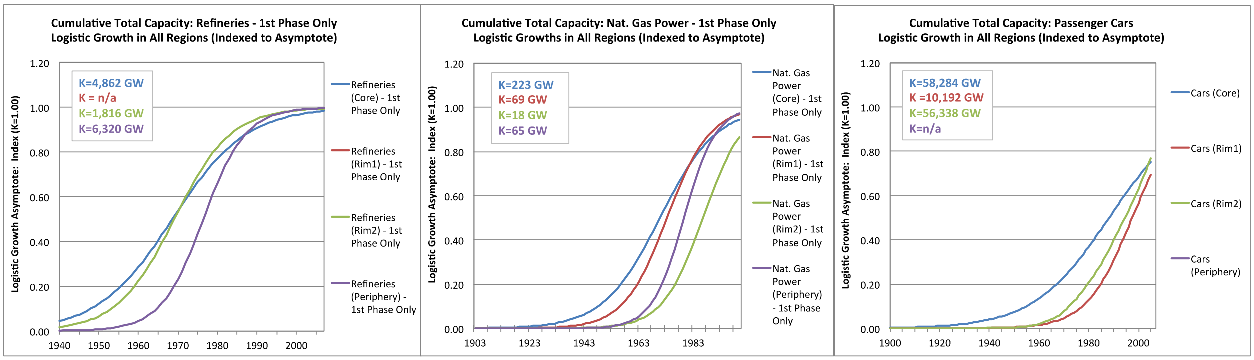

FIGURE 4. RATE & TIMING OF CAPACITY GROWTH AS TECHNOLOGIES DIFFUSE SPATIALLY. NOTES: LOGISTIC GROWTH FUNCTIONS FITTED TO CUMULATIVE TOTAL CAPACITY DATA AND INDEXED SO EACH ASYMPTOTE (K) = 1.00 (ABSOLUTE VALUES OF K SHOWN IN BOXES). DATA WHERE AVAILABLE FOR ALL REGIONS (CORE, RIM1, RIM2, PERIPHERY) FOR REFINERIES (LEFT PANEL), NATURAL GAS POWER (CENTRE PANEL), PASSENGER CARS (RIGHT PANEL). SEE WILSON, 2009 FOR DETAILS.

With the cumulative total capacity data, it was not possible to test whether these increases in rates (decreases in durations) as technologies diffused spatially was also associated with a decrease in the pervasiveness of diffusion as the core, rim and periphery regions are of different sizes. However, Figure 5 does show a steepening or 'acceleration' of the extent - duration relationship (shown previously in Figure 2) from core to rim to periphery regions. This is consistent with the general finding of more rapid but less pervasive growth as technologies diffuse spatially.

Figure 5 plots the extent of diffusion (normalised K) against the duration of diffusion (Δt) for all the data points available. The number of data points decreases from core to rim to periphery as capacity growth is more likely to be still exponential and so not describable by logistic growth functions. However, the steepening of the K - Δt relationship is clearly evidenced, with increasing exponents in the best fit lines for the data points in the core, rim1 and rim2 regions. (No best fit line is shown for the periphery region which has only 3 data points). As technologies diffuse spatially, a given extent of growth requires a shorter duration of growth.

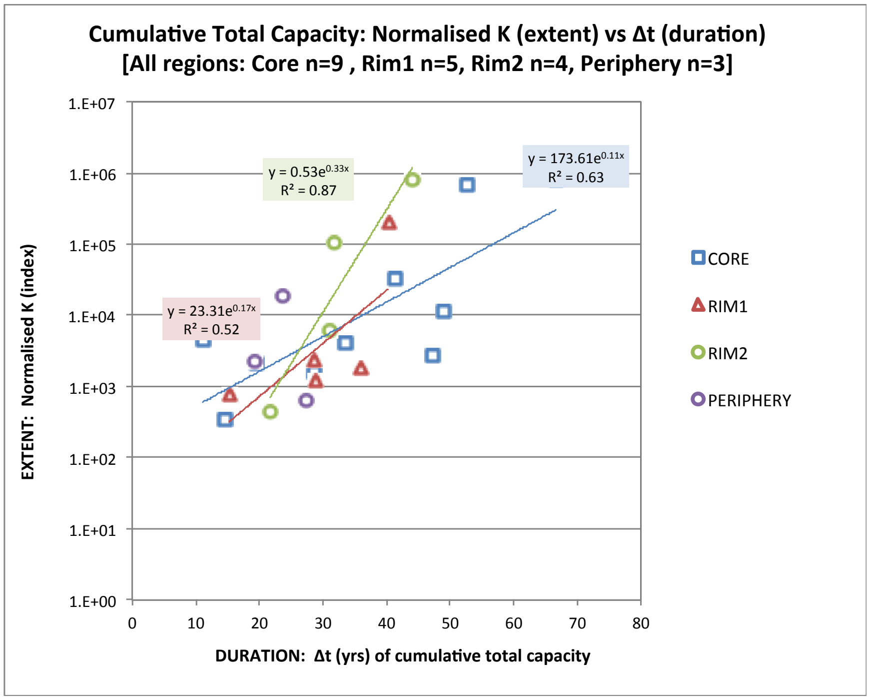

FIGURE 5. EXTENT – DURATION RELATIONSHIP OF CAPACITY GROWTH AS TECHNOLOGIES DIFFUSE SPATIALLY. NOTES: DATA POINTS SHOW LOGISTIC FUNCTION PARAMETERS K VS. ΔT FOR ALL AVAILABLE DATA IN EACH TECHNOLOGY'S CORE, RIM1, RIM2 AND PERIPHERY REGIONS. OMITTED POINTS MEAN DATA WERE UNAVAILABLE OR DID NOT DESCRIBE LOGISTIC GROWTH.

3 FINDINGS: INDUSTRY LEVEL AND UNIT LEVEL GROWTH

3.1 Experimentation in the Formative Phase of a Technology's Lifecycle

The industry level growth dynamics shown in the previous section conceal a series of phases in a technology's overall lifecycle from origination and development through to deployment, widespread diffusion, and ultimately, senescence. Here, the emphasis is on the commercial deployment of technologies which begins with a 'formative phase' during which a technology is iteratively tested, refined and adapted to market conditions (Jacobsson and Lauber, 2006).

The formative phase of a technology's commercial deployment describes the critical period between the development of an innovation and the emergence of positive feedbacks or 'cumulative causation' which sustain its diffusion (Jacobsson and Bergek, 2004). The formative phase is characterized by experimentation, "*an iterative process of understanding what doesn't work and what does*", encompassing both success and failure (p2, Thomke, 2003). Ruttan (2001) calls this "*debugging*" through a process of "*designing-by-experience*".

Experimentation thus involves a repeated and iterative testing and modification of technologies to improve their performance, reduce their cost, and adapt them to specific market demands based on feedback from end users. This typically takes place in market niches which offer some protection from competitive pressures (Kemp et al., 1998). Market niches for low carbon or efficient end-use technologies are often created or sustained by public policy (Schot and Geels, 2008). The formative phase is also important for building expectations for a technology's future diffusion trajectory, providing a means of "articulating" the designs, markets, policies, and end-user demands of a technology (Kemp et al., 1998).

3.2 Formative Phase Growth in Unit Numbers but Not Unit Sizes

Figure 6 explores changes at the unit level during the formative phase of energy technologies' diffusion. Specifically, changes in the *numbers* of units over time are contrasted with changes in the *sizes* of units over time. Figure 6 shows data for both steam turbine units in coal-fired power plants (left panel) and wind turbines (right panel) as examples of the general pattern observed. The blue lines show changes in the numbers of additional units installed each year; the red and green lines show changes in the average and maximum capacities of those units respectively. In both cases, the data describe diffusion in each technology's core region: the OECD in the case of coal power; Denmark in the case of wind power. For wind power, the commercial history of new wind turbine models developed by Vestas, the leading Danish (and global) manufacturer, is used as an approximation of maximum unit capacities. The observable up-scaling of turbine capacity is still far from saturation, particularly in the offshore market segment for which 5MW and larger unit capacities are envisaged (GWEC, 2008).

Figure 6 shows how the initial period of diffusion at the industry level is characterized by only small increases in unit capacities (red lines, right-hand y-axis) but steady, albeit fluctuating growth in the numbers of units installed (blue lines, left-hand y-axis). The processes of experimentation described above occur therefore using increasing numbers of small-scale units. This formative phase *precedes* the up-scaling or increase in unit capacities of technologies in commercial settings: building many before building big. This sequence from the formative phase to the up-scaling phase is indicated on the graphs. The up-scaling phase is characterized by a rapid and sustained increase in unit size, particularly when considered at the scale frontier (green lines, left-hand y-axis).

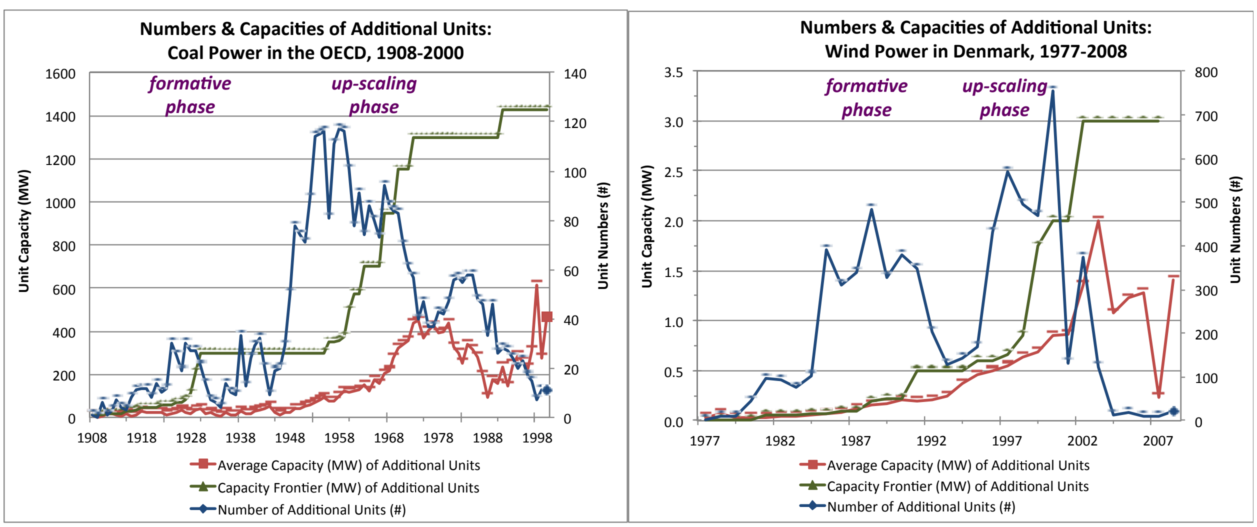

FIGURE 6. CHANGES IN UNIT NUMBERS AND UNIT CAPACITIES FOR COAL POWER (LEFT PANEL) AND WIND POWER (RIGHT PANEL). NOTES: DATA FOR COAL POWER FROM PLATTS, 2005; DATA FOR WIND POWER FROM DANISH ENERGY AGENCY, 2008.

The process of experimentation with many small-scale units is further illustrated in Table 3 which compiles available data from the energy technologies analysed in their core regions (which vary geographically and in size). Technologies are ordered from top to bottom according to how long ago they began diffusion. The right-hand column shows the number of years and number of units built during a formative phase which is measured from first commercial deployment to the point at which new units reach 10% of the eventual unit scale frontier.

An extended period of experimentation with many small-scale units should mean these formative phases last several decades and involve the deployment of many units. This is indeed the case. Nuclear power is the outlier with a relatively short formative phase and relatively few numbers of units built prior to up-scaling. But in fact, this exception supports the generalizable rule. The unit scale frontier of nuclear power increased five-fold in the decade that followed commissioning of the first 50 MW commercial reactor in 1956. Ultimately, these rapid increases in unit size were a contributing factor to the rising complexity that created diseconomies of scale and constrained further growth of the industry in the late 1970s (Grubler, 2010; Lovins et al., 2003).

TABLE 3. FORMATIVE PHASES OF ENERGY TECHNOLOGIES: DURATIONS & NUMBERS OF UNITS.

Technology	Initial Market	First Commercial Capacity Installed	10% of Maximum Unit Scale Reached	Formative Phase: No. of Years | No. of Units
Hydro Power	OECD	<1900s	1934	40 years | 3500 units
Natural Gas Power	OECD	1900s	1948	50 years | >400 units
Coal Power	OECD	1900s	1950	50 years | >775 units
Nuclear Power	OECD	1950s (1940s*)	1963	10 years | 25 units
Wind Power	Denmark	1970s (1880s*)	1987	15-100 years | >1400 units
*Refineries***	*US*	*1860s-1870s*	*(1948 - average capacity only)*	*(80-90 years | >500 units?**)*

* First nuclear installations on submarines date to 1940s; first wind power generators date to 1880s, but from 1970s in their modern form.
** Refineries data are indicative only. Saturation capacity measured in terms of average rather than maximum capacities; number of units are a rough estimate.

4 FINDINGS: UNIT LEVEL GROWTH

4.1 Up-Scaling Driven by Economies of Scale at the Unit Level

'Up-scaling' is an increase in the capacity of an individual technological unit to convert energy into a useful service. Historical examples of up-scaling were given in Figure 1. Up-scaling is typically associated with economies of scale which describe reductions in average unit costs as the size of individual units ('unit' scale economies) or the volume of total production ('manufacturing' scale economies) increase over the long run, i.e., assuming all production inputs are variable.

Figure 6 illustrates the up-scaling phases for coal power and wind power in their respective core regions (see also Figure 1). After a fifty year formative phase, the maximum size of steam turbine units in coal-

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fired power plants in the OECD increased by an order of magnitude from 300MW to 1300MW over an 18 year period from 1955 to 1973. (The average size of new units increased from 100MW to 400MW over the same period). This followed a formative phase of around five decades during which maximum unit capacities did not exceed the 300MW unit installed in 1930.

Wind power makes an interesting comparative case as, like coal power, economies of scale at the unit level might be expected to drive significant and rapid increases in unit capacities following the maturation of the formative phase. Larger turbines allow longer blades with more than proportional increases in power output, and the further benefit of stronger, more laminar winds at higher hub heights. Despite, this economic incentive for up-scaling, the right panel of Figure 6 shows how the unit scale frontier of wind turbines in Denmark increased very little during a formative phase lasting two decades from the late 1970s. The period of rapid up-scaling was then concentrated in a 6 year period from 1997 to 2002 during which the largest Vestas turbines increased in capacity from 0.7MW to 3MW, and the average capacities of all turbines installed in the Danish electricity system increased from 0.5MW to around 1MW.

As documented in the case study on wind power, in contrast to this Danish experience, countries like Germany, Sweden, and Netherlands placed early emphasis on rapidly increasing turbine capacities to capture unit scale economies (Åstrand and Neij, 2006). Relative to the Danish case, this premature move to the up-scaling phase failed to build an enduring industry (Meyer, 2007). As Heymann (1998) puts it: *"The problems in wind technology development [in Germany and the US] demonstrate that the testing, design improvement, and maturation of complex technologies require much practical experimentation and at least as much time, money, and effort as do the initial design and construction"* (p667). In the successful Danish case, up-scaling occurred only once the fundamental design issues with the technology, which were being addressed during the formative phase, were settled.

4.2 Up-Scaling Influenced by Market Demand for Different Size Units

Figure 7 shows the up-scaling dynamics for the full sample of energy technologies analysed distinguishing growth in average unit capacities (left panel) from growth in the unit capacity frontier (right panel). Each line describes the changes over time of the capacity in MW of newly installed 'units': steam turbine units in coal, gas and nuclear power plants; turbine units in hydro power plants; wind turbines in wind farms; jet engines in passenger aircraft; internal combustion engines in cars; and compact fluorescent light bulbs in lighting systems.

Increases in the maximum size of additional units (Figure 7, right panel) show the relatively short duration of the up-scaling phases of many of the technologies, but particular nuclear power. The unique issues associated with managing nuclear fuel cycles coupled with the need to reduce capital costs drove rapid up-scaling from the mid-1960s to mid-1970s following a relative short formative phase (see Table 3). For refineries only average capacity data were available: up-scaling was concentrated during the several decades following World War II. Increases in unit capacities largely saturated by the 1970s. As the largest capacity end-use technology, jet aircraft also exhibited rapid and early up-scaling between the period of first commercial deployment (the Boeing 707-100 in 1958) to the introduction of the Boeing 747-100 in 1969. The recent introduction of the larger Airbus A380 has only slightly extended the unit scale frontier.

Increases in the average size of additional units (Figure 7, left panel) show the market demand for units of different sizes. For technologies with homogeneous market demand – i.e., providing a particular function in a single market niche or segment – increases in the average and maximum sizes of additional units should be similar. In other words, up-scaling characterises all or most new units being installed. This is clearest for nuclear power, wind power, and to a lesser extent, coal power.

For technologies with heterogeneous market demand – i.e., providing different functions in many market niches or segments – increases in the average size of additional units should be slower than increases in maximum size. In other words, up-scaling characterises only some of the new units being installed in those market niches which demand larger units (e.g., due to the availability of economies of scale). This is clearest for natural gas power, hydro power, and a lesser extent, jet aircraft.

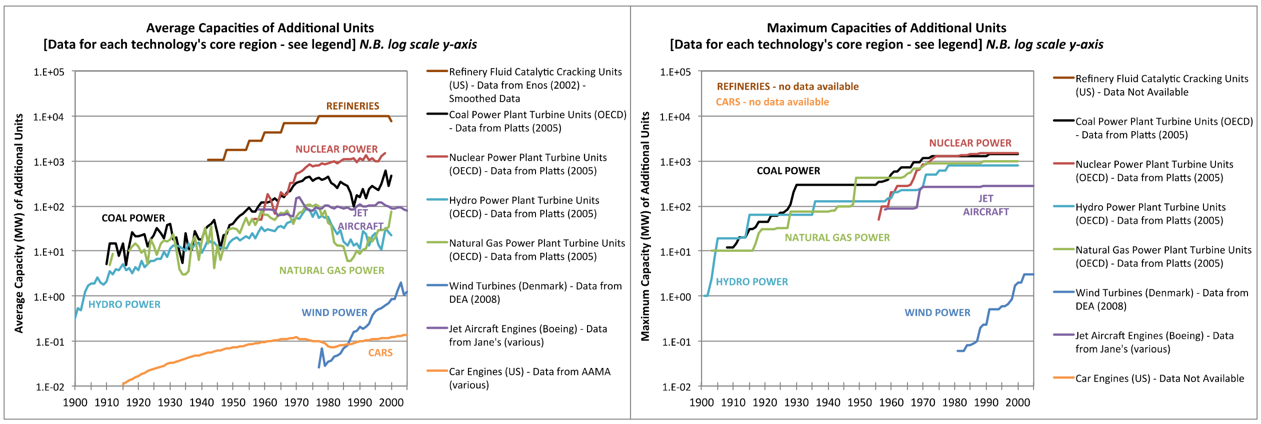

FIGURE 7. UP-SCALING OF ENERGY TECHNOLOGIES SINCE 1900: AVERAGE UNIT CAPACITIES (LEFT PANEL); MAXIMUM UNIT CAPACITIES (RIGHT PANEL). NOTES: SEE FIGURE LEGEND & WILSON, 2012 FOR DATA SOURCES.

4.3 No Evidence for 'Leapfrogging' of Up-Scaling as Technologies Diffuse Spatially

'Leapfrogging' describes the adoption by a developing country of a less polluting or more efficient technology from a developed country thus avoiding a polluting or inefficient part of the developed country's development pathway (Goldemberg, 1998). The evidence for leapfrogging is mixed, and as a result the concept is contested (Perkins, 2003; Gallagher, 2006).

Figure 8 explores the evidence for leapfrogging relating to up-scaling in two different ways using a set of three power generation technologies (coal, nuclear, natural gas).

First, leapfrogging may imply an acceleration in the rates of up-scaling (steepness of the curves in Figure 8) as technologies diffuse spatially. This would be consistent with the spilling over of up-scaling related knowledge generated in initial markets to later markets in which available scale economies could be more readily and more rapidly captured. Second, leapfrogging may imply an increase in the extents of up-scaling (maximum unit capacities shown as K values in the boxes in Figure 8) as technologies diffuse spatially. This would similarly be consistent with knowledge spillovers from initial to later markets, but in this case enabling larger capacity units to be developed and deployed (to the extent these are demanded in particular market segments – see above for discussion).

Neither form of leapfrogging relating to up-scaling was evidenced in the data. Up-scaling rates do not accelerate from core to rim to periphery regions (blue to red / green to purple lines in Figure 8). Nor do up-scaling extents increase from core to rim to periphery regions K values in boxes in Figure 8). Maximum unit sizes in core regions are consistently higher in core regions than in rim2 and periphery regions (excluding the rim1 data for the former Soviet Union). For example, the typical maximum unit capacity of coal power in the OECD (core region) lies somewhere around 1000 MW, in Asia (rim region) around 800 MW, and in the rest of the world (periphery region) around 700 MW.

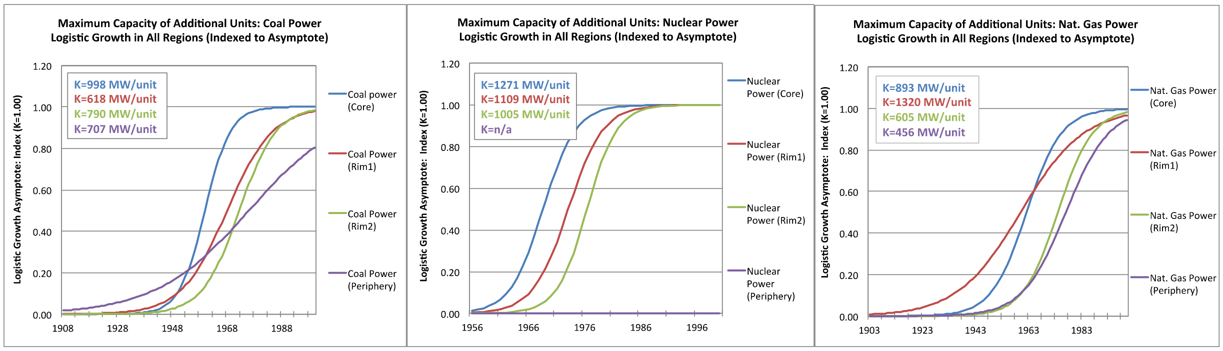

FIGURE 8. RATE & TIMING OF UP-SCALING AS TECHNOLOGIES DIFFUSE SPATIALLY. NOTES: LOGISTIC GROWTH FUNCTIONS FITTED TO DATA ON MAXIMUM CAPACITY OF ADDITIONAL UNITS AND INDEXED SO EACH ASYMPTOTE (K) = 1.00 (ABSOLUTE VALUES OF K SHOWN IN BOXES). DATA WHERE AVAILABLE FOR ALL REGIONS (CORE, RIM1, RIM2, PERIPHERY) FOR COAL POWER (LEFT PANEL), NUCLEAR POWER (CENTRE PANEL), NATURAL GAS POWER (RIGHT PANEL). SEE WILSON, 2009 FOR DETAILS.

This absence of leapfrogging relating to up-scaling reinforces the earlier finding that an initial and often extended formative phase is important for generating the knowledge and institutions needed to design, develop, and increase the unit size of energy technologies. Such knowledge is not fully transferrable from initial market to later markets through spillovers or other forms of knowledge exchange. This implies that too rapid or too early up-scaling in later markets may be infeasible or inappropriate given the absence of necessary supporting conditions developed locally through experience, experimentation and learning (Gallagher, 2006; Dahlman et al., 1987).

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5 CONCLUSIONS

Table 4 summarises the common patterns or growth dynamics observed at both industry and unit levels for the sample of energy technologies analysed.

TABLE 4. COMMON GROWTH DYNAMICS OBSERVED HISTORICALLY IN ENERGY TECHNOLOGIES.

Category	Empirical Finding
Industry Level Growth (Diffusion)	There is a consistent relationship between the extent and duration of diffusion measured in terms of cumulative total capacity.
	The relationship between the extent and duration of diffusion accelerates as technologies diffuse spatially out of their initial markets: the time taken to reach a given level of cumulative total capacity decreases.
Industry Level & Unit Level Growth	Diffusion begins with an often extended formative phase, involving experimentation with many small-scale units.
	Knowledge generated during the formative phase underwrites subsequent increases in unit size (up-scaling).
Unit Level Growth (Up-Scaling)	Up-scaling is more rapid for technologies with clear economies of scale. Up-scaling in terms of average unit capacities is less rapid for technologies which service different market demands.
	There is no evidence for 'leapfrogging' relating to up-scaling as technologies diffuse spatially. Knowledge spillovers do not enable later markets to up-scale energy technologies more rapidly.

The consistent relationship between the extent and the duration of industry level growth implies a trade-off faced by accelerated diffusion which is likely to result in less extensive or less pervasive diffusion (i.e., lower market penetration). The extended length of the formative phase as a precursor to subsequent unit level growth (up-scaling) as well as industry level growth (diffusion) similarly cautions against over-exuberant efforts to compress the timescales needed to ready large-scale energy technologies for widespread deployment. Extensive diffusion takes time; so too do the knowledge generation processes that underwrite the capturing of economies of scale at the unit level.

These observations from core markets broadly hold as technologies diffuse spatially into later adopting markets. Over the sequence from core to rim to periphery regions, the relationship between the extent and duration of diffusion remains consistent while steepening: knowledge spillovers enable faster diffusion in later markets. Up-scaling, however, does not similarly accelerate. Later adopting regions need time to develop the knowledge, capabilities, and institutions to support increases in the unit sizes of energy technologies.

The findings of this analysis of the historical diffusion and growth of a sample of 9 energy technologies are inherently general, and are predicated on technologies that have successfully diffused and that are mature enough to have exhibited signs of saturation (and so logistic growth). Given also the limited scope of the historical data set, generalising findings beyond successful, mature technologies in core markets should be cautious.

6 FURTHER READING

This case study extends a body of research begun in Wilson, 2009 and more recently applied to learning and formative phases historically (Wilson, 2012), and to the evaluation of future scenarios of technological diffusion (Wilson et al., 2012). For a more general overview of the dynamics of technological change and diffusion in the energy system, see Grubler et al., 1999 .

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